

# Potentialities of HTS superconductor technology in telecommunication satellites

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**Résumé :** Deux démonstrateurs d'équipements spatiaux pour satellites de télécommunications, utilisant des composants supraconducteurs à haute température critique et de l'électronique refroidie sont présentés : le premier concerne 24 récepteurs RF destinés à équiper le plan focal d'une antenne FAFR en bande Ka, le second porte sur la réalisation d'un IMUX de 60 canaux en bande C.

**Abstrat :** Two proof-of-concept using high temperature super-conductive technology and chill electronics for telecom satellites are investigated: the first is a front end assembly with 24 receivers for FAFR Ka antenna and the second is a 60 channel IMUX filter in C band.

## 1. Introduction

High temperature super-conductive (HTS) technology is presented as a disruptive technology able to improve the performances of microwave equipment: mass and volume savings, electrical properties, etc.

To verify the well-founded of these qualities for telecom satellite payloads, the research department of Alcatel Space has studied two proof-of-concept of microwave space equipment including super-conductive and chill electronics. The objectives of these projects are to estimate the potential of HTS technology, evaluate the impact of the cryo-system on the satellite platform, determine the threshold of interest and estimate the development duration between the state of art and future credible equipment for commercial applications.

In this paper, HTS is based on super-conductive thin film material. The material is YBaCuO or TlBaCuO deposited on LaAlO<sub>3</sub> or MgO substrates. The reduced microwave resistivity of HTS thin films compared to copper allows realizing micro-strip or coplanar resonators and lines which are more compact than classical cavity resonators. Super-conductive micro-strip has a quality factor equivalent to the one of a bulk resonator in C-band.

Thin films are etched to obtain elementary resonators and mutual coupling between resonators. The steady progress of electromagnetic simulation software associated with the reproducibility of etching process is a way to make up filters without the tedious resonator tuning inherent to bulk filters and reduced the manufacturing cost.

In association with HTS device, cooling permits the introduction of chill electronics in the equipment. It is known that operating at low physical temperature decreases the noise factor of radio frequency amplifier (LNA).

The dark side is the need of a cooling system to provide the low temperature to the filter. Because the super-conductive phenomenon appears at low temperature and is operating around 75 K in YBaCuO material and 85 K for TlBaCuO. Therefore the HTS devices must be contemplated only for units where there is a high number of cold devices to justify the

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investment in a cryo-system. The mass and size reduction on HTS filters, combined with the improvement of performances shall overpass the drawback of a cryo-system.

## 2. HTS filtering potential

HTS allows reintroducing micro-strip technology for implementing sharp RF filter. The main interest is to reduce the size of the filter. .

Figure 1 shows the topology of an elliptic 8 poles self-compensated filter based on a Alcatel Space patent [3]. Figure 2 represents it measured frequency response at 77 K. The superconductor material is YBaCuO deposited on LaAlO<sub>3</sub> substrate. The surface of the filter is as low as 21 x 12 mm. The quality factor of a elementary resonators is around 12000.

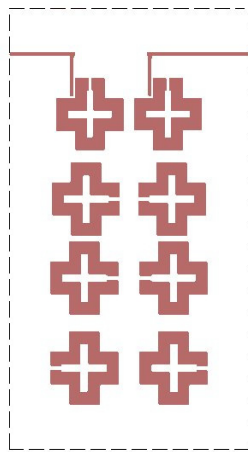


Figure 1

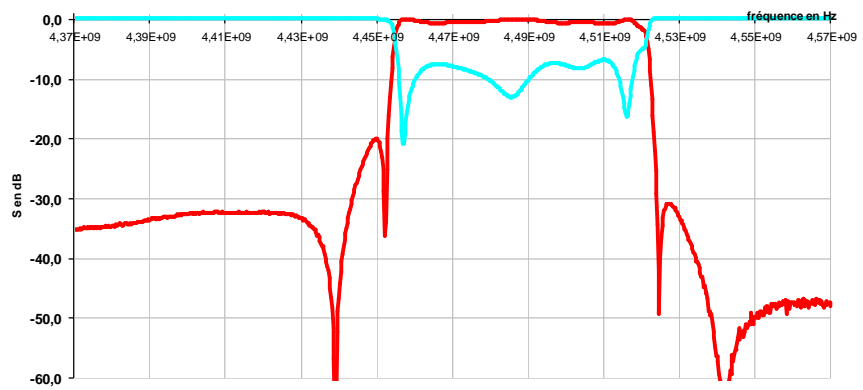


Figure 2

## 3. The demonstrators

The benefits of HTS technology were experimented on two RF demonstrators for different applications.

**The first project, SERACS** (Système à Eléments Récepteurs Actifs Cryogénique et supraconducteur) is the focal array of a receiving antenna (FAFR). The target application is a receive multi-beam satellite antenna in Ka-band. Small ground terminals with low emitted power are wished by the final users. In fact, the short link budget and the frequency reuse require a multi-beam antenna with a high G/T. The target demonstrator is for a 24 beams antenna.

The proof-of concept is constituted of three volumes that are delimiting different temperature areas : a relatively hot area for the radiating elements (1), a cold area with the super-conductive filters (2) and an intermediate temperature area with the LNA (3).

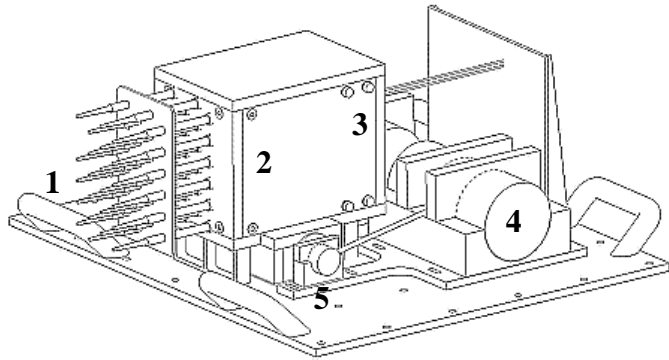


Figure 3 : Global view

The temperature in the three areas is controlled by two autonomous Stirling cryo-coolers in redundancy . The heat rejected by compressors (4) and cold fingers (5) is transmitted to a base plate that simulates the satellite heat pipe. The proof of concept has 39 cm of length, 27 cm of high and 17 cm of width. An optimisation would allow reducing the length. However, the height and width are imposed by the source location in the focal plan.

The mass is not representative of a final equipment because the cryo-coolers are oversized for the project. They have been taken off the shelf without any optimisation.

The mechanical positioning and the thermal isolation between inside volumes and between inside and outside are obtained with a specific material developed during the project (ALCATEL patent). This material is light weight (4 kg/m<sup>2</sup>) and has good structural properties. Its thermal isolation is equivalent to a standard multilayer isolation (MLI) of three layers. The radiative isolation with the outside environment is performed by a 20 layer MLI attached to the structure.

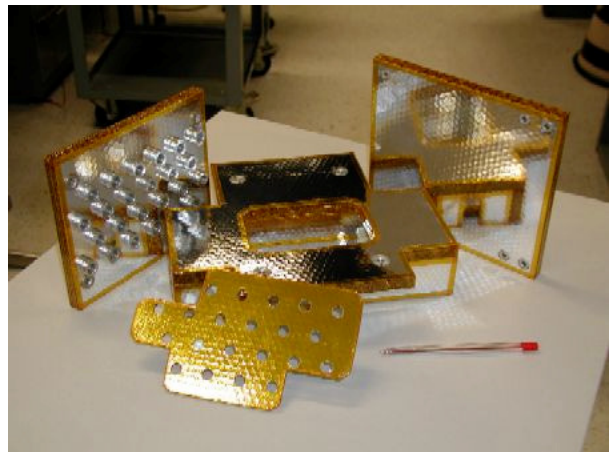


Figure 4

To perform the tests, the demonstrator has been placed in a vacuum chamber. In orbit conditions, worst case of solar flux was simulated by radiating surfaces (black body) at 370 K placed in front of the equipment.

Three temperatures can be controlled independently, i.e. the black body, the environment temperature and the cryo-cooler reject temperature, thus allowing to simulate different operational conditions

Next figure presents the demonstrator in the vacuum chamber with its complete thermal isolation.

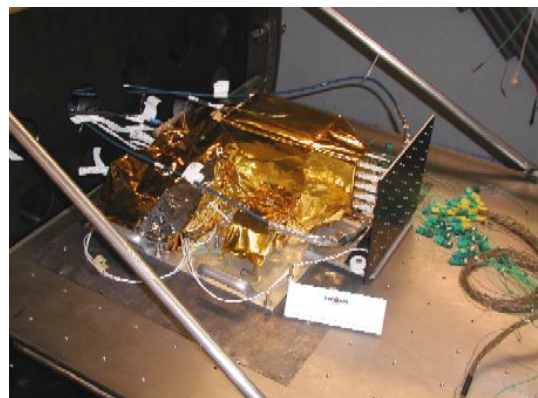


Figure 5

The demonstrator has been tested continuously during 10 days. In nominal conditions (worse solar flux, half of the amplifiers on and a simultaneous working of two cryo-coolers at intermediate power), we have measured the following temperatures:

Radiating elements temperature	374 K
Temperature of warmer filter	78 K
Temperature of warmer LNA	168 K
Cold finger reject temperature	324 K
Environment temperature	293 K

With the knowledge of the electrical power consumption (163 W) and the efficiency of the cryo-cooler, the cold need was evaluated around 6.2 W, close to the prediction. After analysing the performances of the concept, we estimate a cold need of 5 W can be enough with an optimised design in worse case of solar flux.

The **G/T improvement** is evaluated at **2 dB** in comparison with a state of art solution without cryogenic. It is a significant improvement for the link budget with user terminals.

It can be pinpointed that 2 dB is the gain obtained by the introduction of **efficient Turbo Coding** compared to classical coding scheme. With additional 2 dB, the end user can **increase the useful bite rate by a 1.6** factor with a equivalent emission power of his ground terminal.

**In this second project**, the target application is a future multimedia Ka-band mission where the satellite realises simultaneously the broadcast between gateways and ground terminal users and the return way between terminal and gate ways (double hop). It is easier to realise the repeater after a down conversion of Ka signals in C band. The useful band is divided in channels of 56.25 MHz and the filtering constraints to separate the channels are high. Based on this scenario, the proof of concept is a 60 channel input demultiplexer (IMUX).

The demonstrator is made of a cold box (6) held in a dish (7) that supports the input and output connections and the cryocooler cold fingers (8). The dish drains the heat rejected to the satellite heat pipes located under the equipment.

The view shows the equipment in flight configuration.

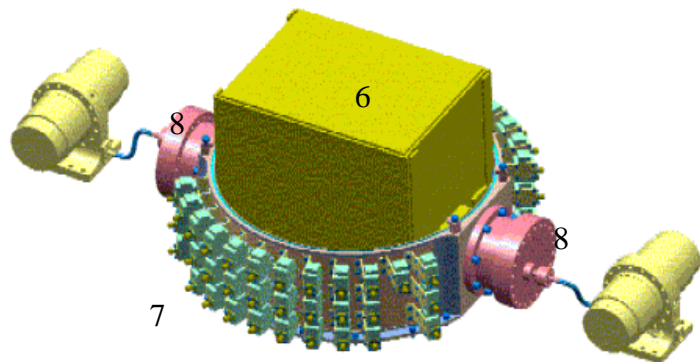


Figure 6

The demonstrator manufacturing is on going. The expected characteristics at design review are:

Mass	
Chill unit	7.5 kg
MPTC	2 x 2800 g
MPTC electronic	2 x 750 g
Total	≈ 15000 g

Size	
Foot print	0.26 m <sup>2</sup>
Volume	45 liters

Thermal statement				
Situation	Cold finger temperature	Reject temperature	Cold power	Electric power
YBaCuO filter 2 MPTC at 50 %	74 K	323 K	1,15 W	60 W
YBaCuO filter 1 MPTC at 100 % and 1 MPTC 0 %	74 K	323 K	1,52 W	96 W
TlBaCuO filter 2 MPTC at 50 %	84 K	323 K	1,15 W	52 W
TlBaCuO filter 1 MPTC at 100 % and 1 MPTC 0 %	84 K	323 K	1,52 W	70 W

The demonstrator is equipped with two cryocoolers in self redundancy. In nominal case, each cryo-cooler runs at mid power and in case of a failure of one cooler, the second can compensate by a operating at full power in the worse case of complete breakdown. We suppose that the life time of two coolers operating at 50 % is longer than a system of two coolers one operating at full power and the second one in cold redundancy. The table shows the cold need in nominal case and in worse case. In worse case, the cold need increases because the fail cryo-cooler have thermal leaks that the active cryo-cooler must compensate.

The choice of TlBaCuO instead YBaCuO does not change the cold power need but reduces notably the electric power because the cold finger temperature is higher.

The TlBaCuO case is compatible with the Air Liquide MPTC presented in next paragraph. The YBaCuO case requires a more powerful cryo-cooler to cover the worse case.

By comparison, a 60 channels IMUX made with cavity filter has the footprint of 0.63 m<sup>2</sup> and a mass of 21 kg.

The superconductive technology brings a **mass saving of 30 %** (including cryo-system) and a **footprint reduction of a factor 3**.

With an optimal design, the power consumption will be around **1 W by channel in worse case**.

## 4. Cryocooler

The Pulse Tube is a key technology for enhance the lifetime and to decrease the induced vibrations of cryocoolers for on-board space applications. Since the middle of the 90's, Air Liquide Advanced Technology Division (AL/DTA) is investigating this technology for various cryogenic temperatures and cooling capacities. An advanced Engineering Model of a Miniature Pulse Tube Cooler (MPTC) has been designed [5], manufactured and tested in 2003. This cryocooler has been chosen by Alcatel Space in the IMUX project because this device is representative of future space cryocooler. This cooler has been proven to exhibit high performances, by producing a cooling capacity of 1 watt at 80 K with 35 watts electrical input power to the compressor motor and a thermal heat sinking environment of 20°C [6].

### 4.1. MPTC design and performance

The final Engineering Model (EM) design is shown in the Figure 7. The total length of the MPTC is 480 mm, including 200 mm of interconnecting pipe. The overall mass of the EM is 2.8 kg.

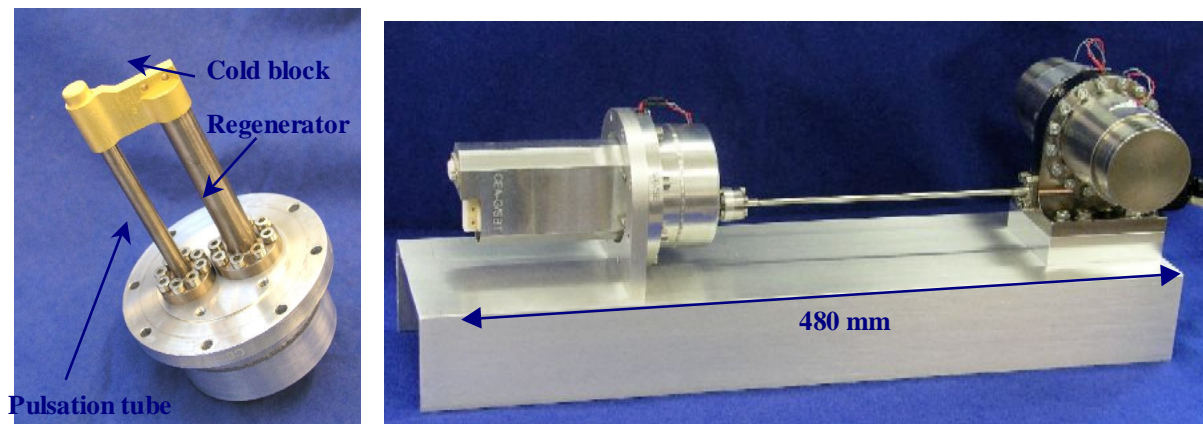


Figure 7 : Pulse tube cold finger (left) and Final assembly of the MPTC Engineering Model (right).

For the Pulse Tube cold finger, the regenerator and the tube are mounted onto a flange in a U-shape configuration. This configuration provides good cryogenic performance in a compact, robust and simple design that improves the integration compared to an in-line configuration. The flange is made of aluminium for thermal heat transfer and mechanical stiffness optimisation. Both the tube of the regenerator and the pulsation tube are made of thin walled titanium alloy Ti-6Al-4V in order to reduce the parasitic heat leaks. The pulse tube EM incorporates a snubber which is used as a launch bumper to prevent any excessive lateral motion of both tubes and to significantly reduce the mechanical stress on the tubes at the flange location. This snubber is also made of aluminium. A low conductivity fiber glass part is placed between the cold block and the snubber cylinder to ensure low parasitic heat losses in case of contact during operation. In normal conditions, there is no contact between the snubber and the cold block of the pulse tube.

The compressor is designed around an innovative moving-magnet linear motor that drives the pistons in a dual opposed configuration into the same compression chamber. The moving magnet linear motor offers big advantages over the conventional moving-coil design. This innovative concept allows placing the coils that are the main source of gas contamination outside the working gas. Additional advantages are the absence of flying leads and glass feed-through to supply current to the coils. Flexure-bearings are used in order to have a radial



clearance between the piston and the cylinder. These flexure-bearings are round discs made of spring steel with 3 arms. With these kind of flexure bearings, a very high radial stiffness can be reached. The coil holders are made of titanium alloy in order to reduce the eddy current losses and to combine high mechanical stiffness and low density. The two compressor halves are mounted on a dedicated nickel plated aluminium alloy “centre plate” that contains all the mechanical, thermal and electrical interfaces of the compressor and the two cylinders. Bolted flanges are directly machined in the titanium alloy block of the coil holder. The gas containment is achieved by means of metallic seals.

Figure 8 presents the performance map of the MPTC plotted for various input powers and applied heat loads for 288 K heat sinking temperature. For 80 K, the design point is 1 W cooling capacity with 35 W electrical input power to the compressor (35 W/W specific power). As shown in the figure, the performance decreases for high input powers due to a decrease of the compressor efficiency and warm up of the compressor and cold finger flanges. The performance also decreases for low applied heat loads due to the predominance of parasitic heat losses. An optimum is found in the 30 to 40 W electrical input power region (design point).

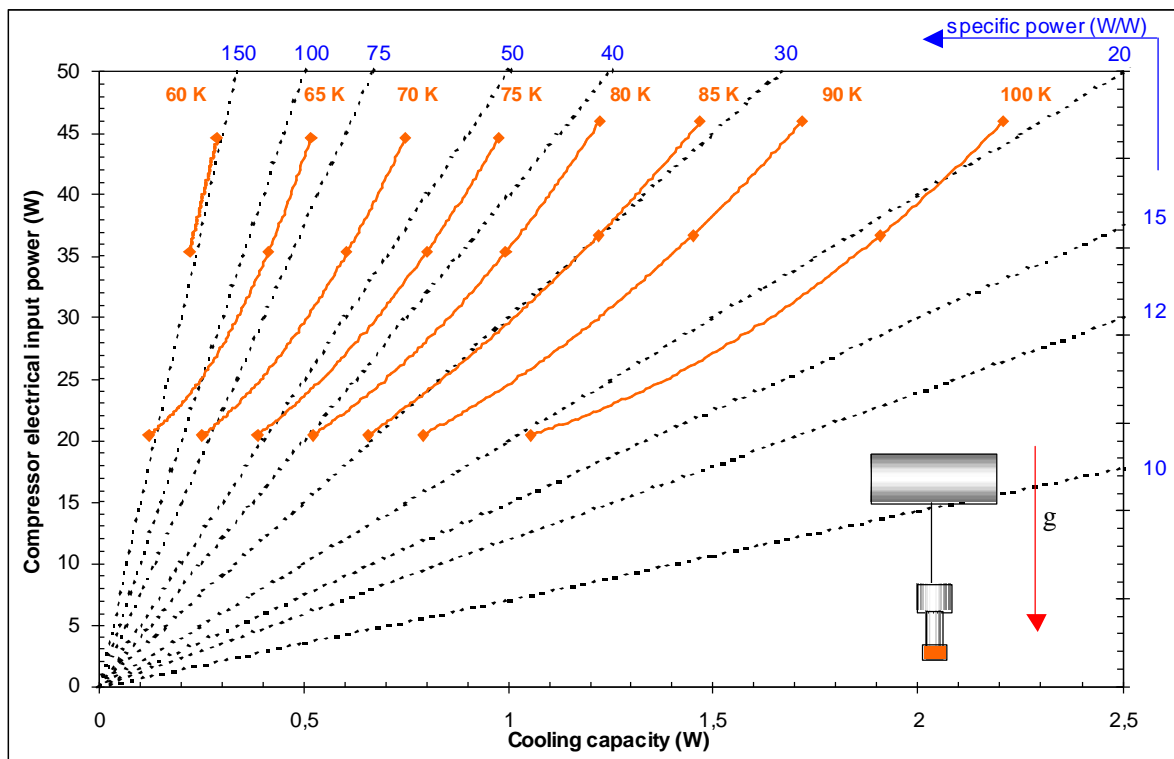


Figure 8 : Performance map of the MPTC (288 K heatsink temperature).

The interface reaction forces produced by the MPTC have been measured directly with force transducers at the mounting interface against a seismic foundation (blocked force approach). Induced vibrations have been directly measured with the quadratic summation of the forces in each of the 3 axes while the MPTC being supplied with a standard drive electronics with no active vibration control. For the fundamental (driving frequency of 50 Hz), the levels are below 0.1 N in the cold finger axis, 0.8 N in the compressor axis and below 0.1 N in the radial axis. It is also demonstrated that the compressor axis level can be drastically reduced (factor of 10) by supplying separately the two compressors motors with a voltage controlled by a vibration output feedback loop (force transducers or accelerometers) for an optimum balance.



#### 4.2. LPTC PRELIMINARY DESIGN AND PERFORMANCES

Taking the advantage of the past pulse tube cooler developments, a large heat lift 40-80 K cooler is under design and optimisation to assess the cooling demand of detectors for the coming Earth Observation applications. The performance objective is to get a pulse tube cooler capable of 2 watts of cooling at 50 K with an electrical input power of 120-140 watts (without electronic driver) and 5 kg mass budget. This performance exceeds by far the performance of US coolers available on the market.

In this way, we are currently working on the tuning of a cold finger breadboard model as shown in figure below. This kind of model makes use of traditional in-line configuration with simple assemblies of stainless steel and copper to ease the prototyping. Figure 9 shows also the evolution of performances for various configurations for constant compression work (107 watt) provided by a compressor tooling. In parallel, a lot of efforts are placed on the compressor design to achieve a compressor efficiency in the 75-80% range.

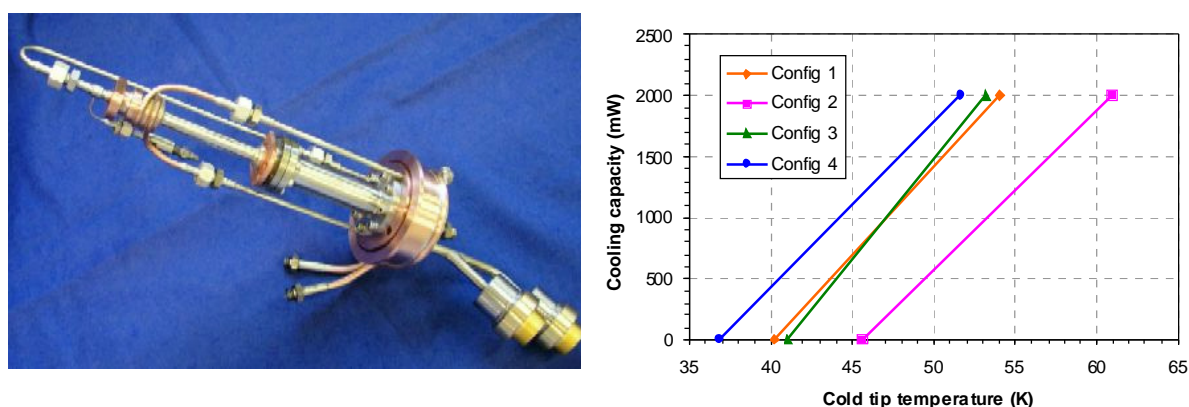


Figure 9 : Pulse tube breadboard cold finger (left) and on-going performances (right).

Based on the information gathered during the prototyping phase, a design of the cold finger engineering model is also worked out. The final design is driven towards a concentric shape (pulsation tube inside the regenerator ring) to enhance the integration and the stiffness of the cold finger. This “Stirling like” design will be compact, efficient and very robust. The final LPTC Engineering Model will be delivered to ESA in the third quarter of 2006, after being submitted to extensive thermal mechanical tests (thermal vacuum testing and launch loads).

Figure 10 shows advanced concentric Engineering Model of the LPTC cold finger

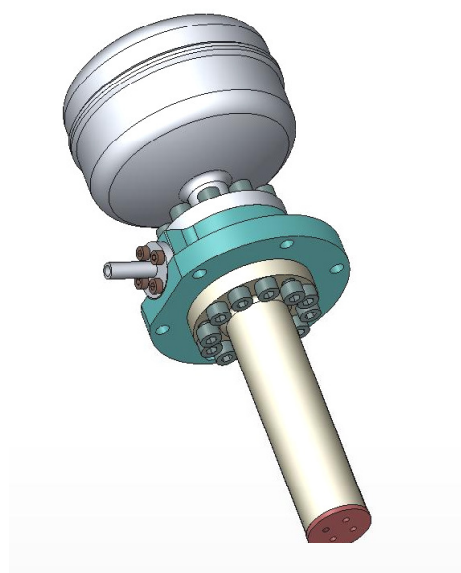


Figure 10

Associated to high reliability flexure bearing compressors the pulse tube cold finger has virtually infinite lifetime, the only remaining failure causes being the pure helium working gas leakage and contamination which are easy to control and/or suppress. Thus, with no moving part in the cold finger, the lifetime of the pulse tube cooler is highly linked to the one of the compressor module. In collaboration with Thales Cryogenics BV, efforts have been made to suppress the main contamination and current lead wire breakage risks by placing the coil outside the helium volume (external static coil and internal moving magnet). Thus, the failure mode analysis is limited to the design of the piston bearings and the alignment procedure inside the cylinders. To get a real piston bearing, a flexure spring (or a stack of) is placed at the front and the rear of the piston. Very high stiffness is provided in radial direction to ensure axial alignment piston/cylinder over the required stroke. An illustration of the flexures is given in Figure 11. Those flexures are carefully controlled and designed well below the fatigue limit of the fully characterised material. Moreover, during the design phase of the flexures, FEM calculations and fatigue tests are performed in parallel. A large number of flexures in a full representative assembly, are tested for more than  $10^7$  cycles for various stress levels (Wöhler fatigue curve, achieved within few days) to support the FEM fatigue calculations.

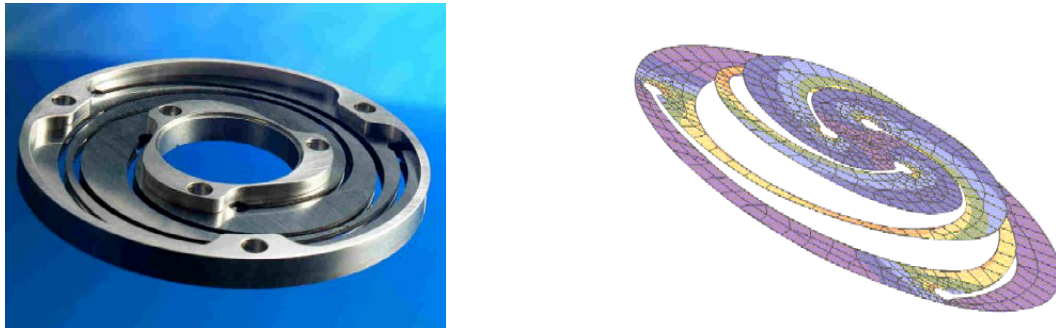


Figure 11 : Example of spring steel flexures with 3 arms

Beside the confrontation of the test results with the simulations, some lifetime tests of the complete coolers are performed on existing Stirling cooler production, as it is done for the high capacity Stirling cooler developed and produced for the CRYOSYSTEM freezers on-board the International Space Station [7].



Figure 12 : CRYOSYSTEM EM Stirling cooler – 8 W @ 75 K / 150 W input power

Two engineering models of such coolers are working under stringent lifetime test profile with 2 cold down / warm up phases per day stressing the internal outgassing of the parts between

75 K and 300 K. So far, each cooler has accumulated more than 15.000 operating hours with no particular degradation which is very encouraging for the enhanced pulse tube technology.

## 5. Conclusions

The learnings of these projects are:

- In Ka antennas, the principal advantages are the reduction of noise factor of active device and the miniaturisation of passive devices. A significant G/T improvement of 2 dB can be achieved.
- The superconductivity reduces by 30% the mass and divides by three the footprint of large RF equipment. For an IMUX in C band, it has been demonstrated that the impact of the Cryocooler is compensated when 60 channels are reached.
- The demonstrators have been defined to be as representative as possible of flight model configuration with same high reject temperature and redundancy strategy.
- The cryo-cooler reject temperature is the parameter that sizes payload impact of the superconductor equipment. Even though the cryo-cooler efficiency is reduced, a high reject temperature (60 ° C / 80 °C) is more favourable because it limits the size and mass of OSR dedicated to the equipment. The on going developments on space cryo-coolers do not yet address this specification.
- The use of TlBaCuO instead of YBaCuO for the superconductor thin film reduces noticeably the cryocooler impact on the payload,
- The Tube Pulse technology seems to have the reliability for long duration missions. The weak point remains to prove this long term reliability by qualify manufacturing methods and ground tests.

These two proof of concept demonstrate the feasibility to design improved space telecommunication equipment based on superconductor technology and chill electronics.

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